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Economic analysis of the contribution of photovoltaics to the decarbonization of the power sector

J. Hernández-Moro [a], J.M. Martínez-Duart [b,*]

[a] Applied Physics Department (C-XII), Autónoma University of Madrid, Campus de Cantoblanco, E-28049 Madrid, Spain
[b] Applied Physics Department (C-XII) and N. Cabrera Materials Institute, Autónoma University of Madrid, Campus de Cantoblanco, E-28049 Madrid, Spain

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ABSTRACT

An analytical method has been developed for the calculation of the future (2013–2050) reduction of CO_2 emissions by the deployment of photovoltaic (PV) systems according to three Scenarios from the International Energy Agency (2DS, Roadmap and New Policies). Next, we have also evaluated the financial extra-costs incurred in the implementation of the PV systems which would replace the current traditional power generation systems, taking as reference four geographical areas: European Union, United States, China, and the world's average. The established method also allows the comparison of the influence on the extra-costs of the actual electricity mix, as well as the current electricity prices, corresponding to the above regional areas. In these calculations, we have taken into account several frequently ignored factors like solar-cell degradation, emissions attributed to the PV systems life-cycle, and the repowering due to the substitution of the systems after their life-time is reached. Finally, the results of this work can be of interest in energy planning policies related to the contribution of PV technologies for the decarbonization of the power generation system.

Contents

1. Introduction

It is a well-known fact the impressive recent growth of renewable energies for power generation applications. This is especially true in the case of photovoltaics (PV), which with average annual growth rates of around 50% since 2005, has surpassed the most

* Corresponding author. Tel.: +34 660 446909; fax: +34 91 4973969.
E-mail addresses: jorgemoro85@gmail.com (J. Hernández-Moro), martinez.duart@uam.es (J.M. Martínez-Duart).

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optimistic predictions [1]. At present, PV can be considered as a mature technology which in about two or three decades would probably move to the terawatt scale from the present more than 100 GW of global cumulative installed power [2]. Therefore, PV will become an important player in the electricity mix of many countries and is expected to contribute globally with percentages close to 10% by 2050 [3]. In addition, PV solar cells constitute probably the best example illustrating the technology-learning process characteristic of large-scale production economics, with a learning rate of 21% since the mid-seventies [4]. As a consequence, the solar module prices have at present plunged below $1 per peak watt, while some Chinese companies are already announcing prices of about half for 2015.

One of the main interests in the deployment of renewable energies in the power sector is related to the curtailment of CO_2 emissions. In effect, CO_2 and other greenhouse-gasses (GHGs) emissions, which in 2012 amounted to about 34 Gtonnes (Gt), are the main cause of global warming and climate change [5]. Evidently, if efficient measures are not taken during the next one or two decades, emissions will continue to rise at an annual rate of 2.5–3.0%, as a consequence of the continuous growth (close to 2%) of the world's primary energy demand [5]. Detailed studies by the Intergovernmental Panel on Climate Change (IPCC) indicate that, in order to avoid a global warming not greater than 2 °C by 2050, it would be necessary not to surpass the mark of 450 ppm in atmospheric C-concentration [6]. The IPCC document also indicates that this stabilization at 450 ppm would require that the peak in the annual emissions should occur within the next 10–15 years at the latest. This is a very challenging objective since we have already surpassed the 400 ppm mark in 2013 [7].

The object of this article is two-fold; first it consists in the development of an analytical method for the calculation of the avoided CO_2 forthcoming emissions by the deployment of photovoltaics in the power sector, and, second, in the calculation of the financial extra-costs incurred, both annually and totally, for any period of time considered, until 2050. Besides, we show in this work how the model can easily be applied to any geographic region and scenario considered for the PV deployment.

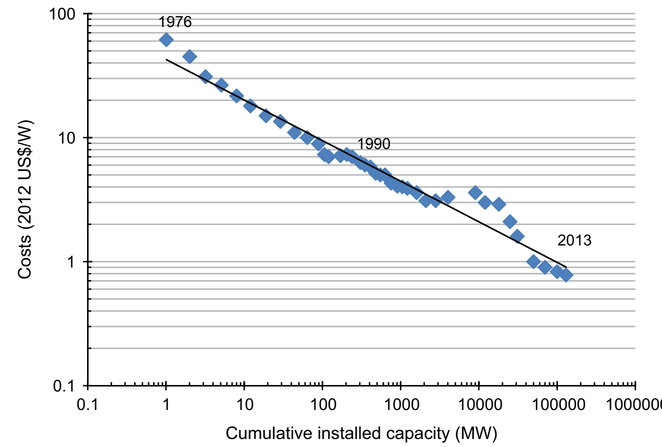

Fig. 1. Learning curve of the PV modules, showing in a log–log scale the cost of the PV modules (in constant 2012 dollars), between 1976 and the end of 2013, as a function of the PV cumulative installed capacity.

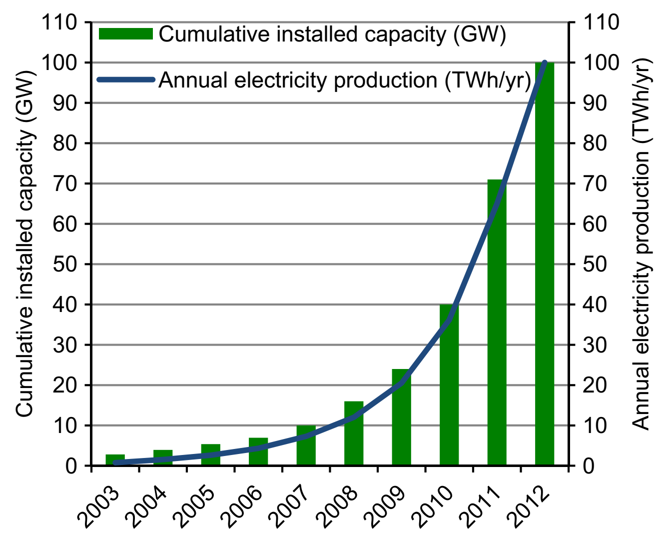

Fig. 2. PV cumulative installed capacity (GW) and annual electricity production (TWh/yr) between 2003 and 2012.

2. Present status and future scenarios of PV power generation

2.1. A short overview and present status of PV power generation

During the last two decades, the deployment of photovoltaic systems for the direct generation of electricity has been quite notable, due mainly to the exceptional decrease in prices and the continuous improvements in solar modules efficiency. The last decade has seen a real fall in the prices of solar cells after the 2003–2006 period, when a silicon shortage and large tariff incentives (cases of Germany and Spain) prevented effective pricing competition [3,8–10]. However, since 2008 there has been a continuous decrease in the price of purified silicon, along with significant cost reductions related to technology learning processes. Consequently, between 2010 and 2012, solar PV power generation costs have fallen around 44% [2,11]. In effect, Fig. 1 shows in a log–log space the cost (in constant 2012 US dollars) evolution of PV modules as a function of the cumulative installed capacity, which yields a learning rate of about 21% [3,4,12].

In Fig. 2 we represent the cumulative installed capacity and the annual electricity production for PV systems during the last decade [2,4,13–15]. It can be observed that the cumulative installed capacity has increased considerably during the last years, with average annual growth rates of 42% between 2000 and 2010 [11] and even 60% between 2007 and 2012 [2]. At the end of 2012 there were 100 GW installed in the whole world [2,3,13], most of them in Germany (32%), Italy (16%), USA (7.2%), China (7%), Japan (6.6%) and Spain (5.1%). However, Europe's leading role is fast diminishing, since its global market share has been reduced from 74% in 2011 to 55% in 2012 [13].

Annual PV electricity production (Fig. 2) has grown analogously to the cumulative installed capacity, reaching 100 TWh/yr during 2012 [11]. In 2011 PV electricity generation represented about 0.5% of the world electricity production [16], whilst for the European Union-27 (EU-27) was 2.6% in 2012 [13], with markedly high contributions in countries like Italy (6.7%), or Germany (5.6%) despite its low solar irradiation.

The PV industry is at present still predominantly based on crystalline silicon solar cells, followed by a share of about 16% of thin-film second generation (2G) cells with somewhat lower prices, as a consequence of the consumption of smaller amounts of materials, the use of large-area deposition techniques and low-cost substrates [3]. In addition, and in order to overcome the Shockley–Queisser limit [17] for single-junction devices, there is at present a large amount of research on third-generation (3G) cells. These cells, which are still under development, can make use of newly developed techniques such as quantum-size effects, two-step processes in intermediate bandgap semiconductors [18], etc.

One of the main goals of PV power generation is to reach grid parity in the near future due to the continued lowering of the cost of photovoltaic systems and the simultaneous increase of prices of conventional electricity. According to one of our previous studies [4], in countries with medium-to-high solar resources grid parity could be reached in about one or two decades, or even earlier if a realistic carbon tax is charged to conventional electricity. A case apart is the one of some islands like Cyprus, Hawaii, or Tenerife [3,19,20] with good solar resources and electricity prices, in some cases up to three times the corresponding continental ones; therefore, in these cases, it can be considered that grid parity has already been reached since frequently a large proportion of the electrical energy, or the fuels to produce it, has to be imported.

One further question to be considered is that solar energy is by its own nature intermittent, i.e., non-dispatchable. For low penetrations in an energy system (below some 20%), PV can usually be easily integrated into the electrical distribution grid. However, for very high penetrations (higher than about 30%), integration techniques based upon several enabling technologies become necessary [21]. As a consequence, there is at present a lot of R&D activities related to energy storage (batteries, supercapacitors, hydrogen, power-to-gas, etc.), smart grids, long-distance power transmission (HVDC), and demand-side adaptive management in order to meliorate the mismatch between production and demand [22], etc.

An emerging concern is related to a possible shorter lifetime, N, of the less costly 2G thin-film solar cells, which are continuously gaining a higher share of the PV market. This is because the levelized cost of PV electricity is very sensitive to N [4]. Therefore, accelerated aging tests of PV modules will have to be developed to ensure that the lifetimes of 2G solar cells are comparable to those of crystalline-silicon ones (about 30 years).

2.2. Future scenarios for PV power generation

We have considered in this work three different PV future scenarios, elaborated by the International Energy Agency, in order to calculate and compare PV implementation for power generation in terms of saved carbon emissions and the financial extra-costs incurred. These scenarios are the 2DS [23,24], Roadmap [25] and New Policies [11]. They have been proposed by the IEA in order to diminish CO_2 emissions, which otherwise could double their present value in 2050 and lead to a global warming of up to 6 °C [23]. In Table 1 we have summarized the objectives for the annual electricity production (E) and the cumulative installed capacity (Q) for the three scenarios considered, where the data for the 2DS and Roadmap Scenarios are given until 2050, whilst for the New Policies Scenario are just until 2035.

The most significant scenario of the three considered in relation to the mitigation of climate change is the 2DS Scenario [23], published in 2012, in which the PV contribution to the global electricity mix in 2050 would be of around 6%. This scenario is an update of the previously well-known Blue Map Scenario [26], published before the unexpected large growth of PV systems installation between 2008 and 2012. The 2DS Scenario [23] sets the target of cutting down energy-related CO_2 emissions by more than half in 2050 (compared to 2009), what would allow to stabilize the CO_2 atmospheric concentration at around 450 ppm, and mitigate global warming to just about 2 °C. For this purpose, annual CO_2 emissions should peak around 2020, at 32 Gt/yr, and thereafter start reducing until reaching 16 Gt/yr in 2050.

The PV Roadmap Scenario [25], published in 2010, is the most ambitious of the three considered in terms of installed power, and the one with more detailed intermediate objectives, which are specified for every decade (see Table 1). This scenario forecasts that in 2050 PV systems would provide around 11% of the world electricity generation.

The New Policies Scenario [11], published in 2012, is the most moderate of the three scenarios considered, and takes account of the broad policy commitments and plans that have been announced by countries, including national pledges to reduce greenhouse-gas emissions and plans to phase out fossil-energy subsidies. The main objective of this scenario is to limit global warming to just 4 °C, which implies stabilizing annual CO_2 emissions around 40 Gt/yr before 2035. Consequently, this scenario predicts that electricity generation from renewables would nearly triple from 2010 to 2035, reaching 31% of the total electricity generation. The contribution of solar PV would be of around 7.5% of the renewables-based generation, and more than 2% of the total power generation in 2035.

Table 1
Annual electricity production (TWh/yr) and cumulative installed capacity (GW) objectives for different years for the three scenarios considered (see text).

Scenario	Variable	2020	2030	2035	2040	2050
2DS	E (TWh/yr)	–	1000	–	–	2655
	Q (GW)	–	800	–	–	2017
Roadmap	E (TWh/yr)	298	1247	–	2907	4572
	Q (GW)	200	900	–	2000	3155
New policies	E (TWh/yr)	332	–	846	–	–
	Q (GW)	267	–	602	–	–

3. Analytical equations for the future electricity production and the levelized cost of energy

In this section we establish the background needed for the development of the analytical models for the estimations of the avoided CO_2 emissions (Section 4) and the financial extra-costs (Section 5) incurred in the PV deployment. For this purpose we first establish (Section 3.1) the analytical equations that determine the future evolution of the annual electricity production and the cumulative installed capacity, and next (Section 3.2) the future evolution of the levelized cost of energy ($LCOE$) of PV systems for each of the scenarios considered.

3.1. Estimations on the future evolution of PV electricity

In this Section we assign analytical closed-form equations to the annual PV electricity production $E(t)$ and the cumulative installed power $Q(t)$, for a year t between 2013 and 2050, for both the 2DS and Roadmap Scenarios, and until 2035 for the New Policies Scenario. In effect, this will allow us to directly calculate and plot the results of $Q(t)$ and $E(t)$ (Sections 4 and 5) in a continuous and accurate way. We have considered the beginning of 2013 as the reference year, when the values of $E(t)$ and $Q(t)$ were approximately 100 TWh/yr and 100 GW, respectively (see Fig. 2). Using these data, and the intermediate and final objectives of $E(t)$ and $Q(t)$ for the three scenarios considered, represented in Table 1, we next assign the analytical equations that best fit those objectives. For our simulations of $E(t)$ and $Q(t)$ we frequently make use of the logistic function ("S-shaped curve"), whose expression for the annual electricity production for a year t, after 2013, would be [27,28]:

$$E(t) = \frac{e^{r(t-2013)}}{(1/E(0)) - (1/M) + (e^{r(t-2013)}/M)} \tag{1}$$

where $E(0)$ is the initial value, i.e., the PV annual electricity production at the beginning of 2013, M is the maximum value of $E(t)$ and r the growth factor. In addition to the logistic function, we also eventually make use of polynomials, as observed in Table 2.

Table 2
Specific parameters for the future evolution of the annual electricity production $E(t)$ and the cumulative installed capacity $Q(t)$ for the three scenarios considered (see text).

Scenario	Variable	Function	Parameters of $E(t)$ and $Q(t)$
2DS	$E(t)$	Logistic	$E(0)=100$ TWh/yr; $M=2850$ TWh/yr; $r=0.16$
	$Q(t)$	Logistic	$Q(0)=100$ GW; $M=2200$ GW; $r=0.145$
Roadmap	$E(t)$	2nd Grade polynomial	$E(t)=2.429\ \text{TWh/yr}(t-2013)^2+34.802\ \text{TWh/yr}(t-2013)+100\ \text{TWh/yr}$
	$Q(t)$	2nd Grade polynomial	$Q(t)=1.6657\ \text{GW}(t-2013)^2+23.767\ \text{GW}(t-2013)+100\ \text{GW}$
New policies	$E(t)$	Logistic	$E(0)=100$ TWh/yr; $M=900$ TWh/yr; $r=0.22$
	$Q(t)$	Logistic	$Q(0)=100$ GW; $M=650$ GW; $r=0.19$

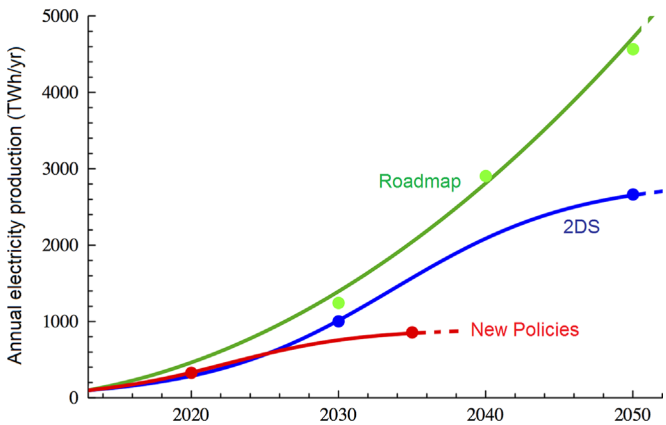

Fig. 3. Suggested curves for the annual electricity production evolution $E(t)$, between 2013 and 2050 for the 2DS (blue) and Roadmap Scenarios (green), and between 2013 and 2035 for the New Policies Scenario (red), together with their intermediate and final objectives (see Table 1). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The analytical expressions of $E(t)$ and $Q(t)$ assigned to each scenario have been summarized in Table 2. In Fig. 3 we present the specific curves from Table 2 for the annual PV electricity production $E(t)$ between 2013 and 2050 for the 2DS and Roadmap Scenarios and between 2013 and 2035 for the New Policies Scenario, together with the objectives for each scenario (see Table 1). We do not show the derivation of the equations for $Q(t)$ since evidently it is similar to the case of $E(t)$.

3.2. LCOE costs future evolution

When estimating the cost of electricity from PV systems, we have to take into account that there are four end-use sectors: (i) residential systems, of up to 20 kW on individual homes; (ii) commercial systems, up to 1 MW; (iii) utility systems, starting at 1 MW and usually mounted on buildings or directly on the ground; and, (iv) off grid applications, that we have not considered in our work. Using the present and future estimations of the shares of the three end-use PV sectors [25] we have estimated that during the 2013–2050 period, 60% of the systems would be residential or commercial and the remaining 40% would correspond to the utility sector.

In a typical PV system, the modules represent around 50–60% of the total cost, whilst the remaining 40–50% corresponds to the BOS (inverter, mounting structures, cabling, etc.) [23,26,29,30]. These ratios will remain practically constant over time, and consequently, besides the module, the BOS components represent one of the main potential sources for further PV system cost reduction. Crystalline-silicon (c-Si) modules prices have fallen from 2 $/W in 2010 to below 1 $/W at the beginning of 2013 [8,30–34]; but besides the module cost, there is still at least another 1 $/W of BOS and installation costs, since BOS costs have ranged from 0.5 to 1.8 $/W [8,24,32,33,35], depending of the region and segment (utility or residential). Furthermore, the final price of the PV system would increase due to the installation labour, interconnection to the grid, etc. which can vary significantly among countries for similar system types. For instance, commercial PV systems are more than twice as expensive in the US than in some European countries like Germany [12,36]. The reasons for these differences are manifold and range from the different legal requirements for permitting, licensing and connection to the grid to the different maturity of the local PV market. Total PV system costs also depend on the specific market segment, being around 30–50% higher for the residential sector than for the utility sector [25,30]. Consequently, taking all these factors into account and using the data available in the literature [12,14,32,36–41], we have assumed in this work a total system cost of 2 and 3 $/W for the utility and the residential sector, respectively. We would like also to remark that these values correspond to the beginning of 2013 (the reference year in our study), and that it represents a kind of world average, even though the prices for some specific regions, case of some European countries [12] can be lower.

Consequently, since we have considered 60% of the systems as residential and 40% as utilities (see above), we have assumed an average PV system cost of 2.6 $/W; besides, this value is in agreement with the one provided by the IEA [11] as the weighted average of costs, for both large and rooftop installations.

The future evolution of the total cost of PV systems will be determined by the learning curve approach, whose learning rate indicates the cost reduction per doubling of the cumulative installed power [4]. PV modules have experienced a learning rate of about 20–25%, while for the BOS components was somewhat smaller, of about 17–22% [4,6,8]. Consequently, we have considered in this work a conservative average learning rate of 18% for the whole PV system, module and BOS included, which is slightly lower than the historical learning rate for both components of the system.

In order to estimate the extra-costs to accomplish the three scenarios considered in this work, we have first to calculate the future evolution of the levelized cost of energy (*LCOE*) for PV electricity. *LCOE* is the method most frequently used when comparing electricity generation technologies or evaluating the economic feasibility of an electric generation project [42–44]. The calculation of the *LCOE* is based on the equivalence of the so-called present value of the sum of the discounted revenues and the present value of the sum of discounted costs. The *LCOE* from PV systems depends heavily on two factors besides the cost of the system, which are the solar irradiation and the discount rate. The discount rate reflects the return on the capital for an investor in the absence of specific market or technology risks [45]. In order to determine the future evolution of the *LCOE* for PV systems we use a model previously proposed by us [4,28], based on the discounted cash flow (DCF) economic techniques and the experience curves approach. All costs in this work are given in

2013 US dollars, so that they are not distorted by inflation rates. According to this model, the *LCOE* for a future year t is given by

$$LCOE(t)=\frac{C(t)+L+\sum_{n=1}^{N}((O\&M+I)C(t)/(1+r)^{n})}{\sum_{n=1}^{N}(STF\eta(1-d)^{n}/(1+r)^{n})} \quad (2)$$

In this equation, the cost of the system for a year t, $C(t)$, is given by

$$C(t)=C(0)\left(Q(t)/Q(0)\right)^{\mathrm{Log}\ (1-LR)/\ \mathrm{Log}\ (2)} \quad (3)$$

where $C(0)$ is the initial cost of the PV system, i.e. in 2013, taken as 2.6 $/W, as explained before. $Q(t)$ is the cumulative installed capacity evolution (see Table 2), and $Q(0)$ is the value of $Q(t)$ in 2013, i.e. 100 GW. LR is the learning rate, taken as 18% for the whole system, including the module and the BOS (as explained before). L is the land costs, and $O\&M$ and I are the operation and management costs and the insurance costs, respectively, expressed as a percentage of the cost of the system. N is the expected lifetime of the system, considered as 30 years [4], and r is the discount rate, taken as 10% for PV systems [45]. S represents the solar resource, which for PV systems has been considered as the global irradiation on a fixed optimally tilted module surface. For comparison purposes we have considered the solar irradiation of the EU-27, USA and China as 1450, 1890, and 1830 kWh/m^2/yr, respectively, which correspond to their population-weighted values of their continents [37]. The seemingly low solar resource corresponding to the European Union is partly due to the contribution of countries like Germany, with relatively low solar irradiation, but with the highest amount of PV installed capacity in the world. We would like also to remark that we have considered population-weighted values, and not just area-weighted values that are even lower [46]. Besides, we have considered a value of 1700 kWh/m^2/yr as the world average solar irradiation. Finally, in Eq. (2), TF is the tracking factor, η the performance factor and d the annual output degradation rate. The rest of the factors in Eq. (2), whose values have not been specified above, have been explained in detail in a previous work [4].

Once we have established the *LCOE*s for PV systems, we have to compare them with the average electricity generation costs of the four regions considered in this work, i.e., the World, EU-27, USA and China. For this we have to take into account that residential and commercial PV systems compete with retail electricity prices, not wholesale prices. Retail prices include, among others, distribution costs, and consequently are almost twice the cost of base-load bulk power. This will allow PV residential and commercial systems to sooner achieve grid parity in those countries characterized by a good solar resource and high conventional electricity retail prices. Taking into account the average wholesale and household electricity prices of the different geographical areas and the appropriate weighting (60% of residential systems and 40% of utility systems) we have estimated average electricity prices of 19.0, 9.8 and 4.8 c$/kWh for the EU-27, USA and China, respectively [8,32,37,47–52]. Besides, we have also considered an average electricity price for the whole world of 11.2 c$/kWh.

Using Eq. (2) we have represented in Fig. 4 the future evolution (2013–2050) of the *LCOE* for PV systems corresponding to the 2DS, Roadmap and New Policies Scenarios (see Table 2). We have also represented, for comparison purposes, the average electricity price for the case of the world, with a real annual electricity price escalation of 0% and 0.5%, although higher increase rates have been experienced in the EU and USA during the last decade [37,49,53,54]. This increase has been expressed in real terms, i.e. discounting the inflation, which has been assumed as 2% [55]; therefore we have really assumed nominal annual electricity price escalations of 2% and 2.5% in this work.

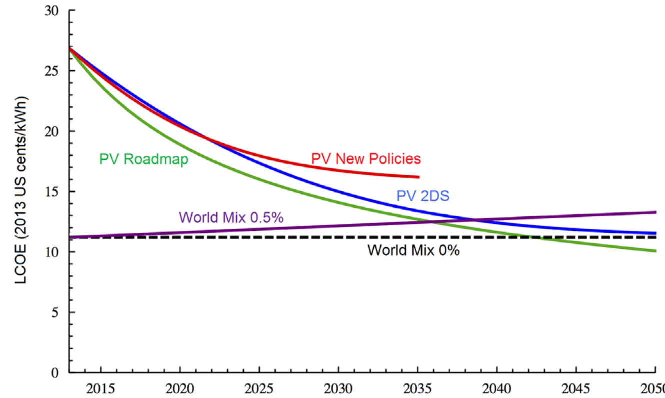

Fig. 4. *LCOE* evolution (in 2013 US cents/kWh) of the new PV systems installed between 2013 and 2050 for the 2DS (blue) and Roadmap Scenarios (green), and between 2013 and 2035 for the New Policies Scenario (red), together with the *LCOE* evolution of the world electricity mix for an annual increase rate of 0% (dashed) and 0.5% (purple). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
CO_2 emissions saved $F(t)$, in gCO_2/kWh, due to PV electricity production for a year t between 2013 and 2050 for the four country/regions considered in this work.

Mix	Associated equation
World (g CO_2/kWh)	$F_1(t)=483+1.0216\cdot(t-2013)$
EU-27 (g CO_2/kWh)	$F_2(t)=301+1.0216\cdot(t-2013)$
USA (g CO_2/kWh)	$F_3(t)=476+1.0216\cdot(t-2013)$
China (g CO_2/kWh)	$F_4(t)=720+1.0216\cdot(t-2013)$

4. Calculation of annual and total avoided CO_2 emissions by PV deployment

The most basic approach to estimate the displaced CO_2 emissions associated with the deployment of PV technology is to use regional "grid averages", which assume that any reduction in electricity demand reduces fuel use in proportion to the average mix of fuels used at the moment for electricity generation. As case studies, we have considered in this work the following countries/regions: European Union (EU-27), United States (USA), China and the world's average. These regions present average CO_2 emissions per kWh produced of 347, 522, 766 and 529 gCO_2/kWh, respectively [56]. The higher associated emissions of the electricity mixes of USA and China, in relation to the EU-27, are mainly due to a larger participation of coal power plants in their mixes, that represents about 42% and 81% of total electricity production, respectively [30,45,48].

We have also considered in our calculations the corresponding emissions associated to the entire life-cycle of renewables, which in the case of PV systems are mainly related to the fabrication processes, as well as O&M of the plants. Current PV associated emissions range between 15 and 80 gCO_2/kW h [6,37,57], and consequently we have taken for 2013 a conservative value of 46 gCO_2/kWh as recommended by the IPCC [6]. We have also assumed that these emissions will diminish in the future, following a linear behaviour, and reaching a value of 8.2 gCO_2/kWh in 2050 [57]. After a few simple mathematical operations, we show in Table 3 the expressions yielding the CO_2 emissions avoided per generated kWh by PV systems, $F(t)$, in relation to the four electricity mixes considered in this work and for any year t between 2013 and 2050.

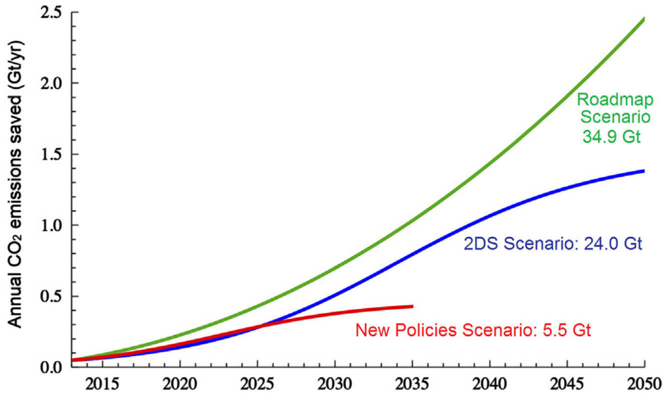

Fig. 5. Annual CO_2 saved emissions, in gigatonnes per year (Gt/yr), between 2013 and 2050 for the 2DS (blue) and Roadmap Scenario (green), and between 2013 and 2035 for the New Policies Scenario (red), due to the installation of PV systems and in relation to the world electricity mix. The total CO_2 emissions saved during the period considered for each scenario are shown under each curve. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

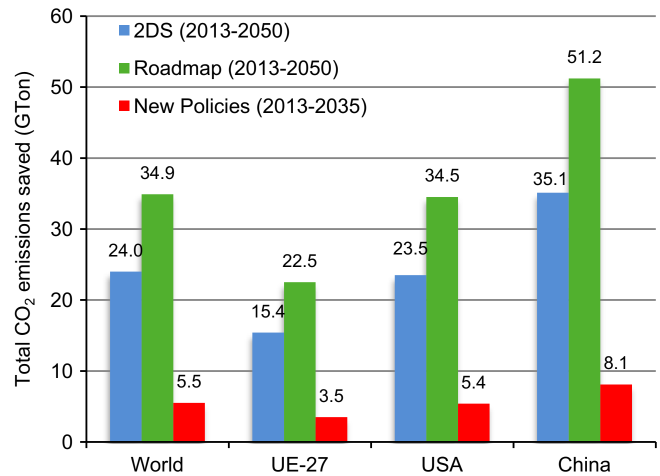

Fig. 6. Total CO_2 emissions saved, in gigatonnes (Gt), during the period 2013–2050 for the 2DS (blue) and Roadmap Scenarios (green) and between 2013–2035 for the New Policies Scenario (red) due to the installation of PV systems in relation to the electricity mix of the world, EU-27, USA and China. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Evidently, the annual CO_2 emissions saved during a year t for each scenario and region considered should be given by

$$CO_2(t) = F(t)E(t) \tag{4}$$

where $F(t)$ represents the CO_2 emissions saved, in gCO_2/kWh, due to PV electricity production for a year t and for any of the four regions considered (see Table 3), and $E(t)$ is the annual PV electricity production for each of the three scenarios considered (see Table 2).

The total amount of CO_2 avoided during the period 2013–2050 for the 2DS and Roadmap Scenarios due to the installation of PV systems would be

$$CO_2 = \int_{2013}^{2050} CO_2(t)dt \tag{5}$$

where for the New Policies Scenario the upper limit of the integral should be replaced by 2035.

Based on the calculations from Eq. (4) we have represented in Fig. 5 the future annual CO_2 emissions avoided due to the implementation of the three scenarios considered for PV systems, for the case of the world average electricity mix. The evolution of the curves corresponding to the rest of the mixes would be analogous to Fig. 5. Evidently, in comparison with this situation, the amount of CO_2 savings would be larger or smaller for the cases of China and the EU-27, respectively, while in the case of USA would be very similar to the case shown for the world. Finally, we have summarized in Fig. 6 the results obtained for the total CO_2 saved emissions, given by Eq. (5), for all the scenarios and regions studied in this work.

5. Calculation of annual and total extra-costs for PV deployment and corresponding unit emission costs

We will establish in this section the expressions for estimating the annual and total extra-costs for PV deployment, in relation to the electricity mixes of the four regions considered in this work (world, EU-27, USA and China), to accomplish the 2DS, Roadmap and New Policies Scenarios. In addition, using these results together with those obtained in Section 4, we will estimate the corresponding unit emission costs associated to PV systems for each scenario and region.

In addition to t, that represents the year between 2013 and 2050 in which the PV systems are installed, we introduce another temporary variable, τ, defined as a certain year of the life of the systems, whose value should be equal or greater than "t", i.e. the year when they were installed, but not greater than "$t+30$", i.e. the year when they reach the end of their expected lifetime. This additional temporary variable is required in order to define the function $E(t,\tau)$, which represents the electricity produced by all the PV systems which were installed at a year t during a certain year τ of their lifetime. Since the average estimated lifetime of a PV system has been taken as 30 years, we should take into account in this function the required repowering of the PV systems once they reach the end of their lifetimes. This is not necessary for the New Policies Scenario, since it only lasts until 2035, but for the 2DS and Roadmap Scenarios, whose periods extend to 2050, we need to consider repowering from 2043 onwards. This is so because a system installed at the beginning of 2013 will be operating, on the average, until the end of 2042 (30 years).

Next, we first determine $E(t,\tau)$ under the most common situation, i.e., when "$t < 2043$" and "$\tau - t < 30$", i.e. before the repowering is necessary. Then, we should have, for the $E(t,\tau)$ function defined above:

$$E(t,\tau) = \left[E(t) - (E(t-1)(1-d))\right](1-d)^{\tau-t} \tag{6}$$

where $E(t)$ and $E(t-1)$ are the annual electricity production, defined in Section 3.1 (see Table 2 and Fig. 3), for a year "t" and "$t-1$", respectively, and d is the annual output degradation rate, whose effect on $E(t,\tau)$ increases as the years "$\tau - t$" pass in relation to the year of the installation of the systems.

Since the systems stop producing electricity after 30 years, then, for "$t < 2043$" and "$\tau - t \geq 30$", we should have

$$E(t,\tau) = 0 \tag{7}$$

When this happens, the new systems have to replace the power lost, and, besides, produce electricity as in Eq. (6) to continue increasing the net PV power generation according to Fig. 3. Therefore, when "$t \geq 2043$", the repowering can be introduced as follows:

$$E(t,\tau) = \left[(E(t) - (E(t-1)(1-d))) + (E(t-30) - (E(t-31)(1-d)))\right](1-d)^{\tau-t} \tag{8}$$

Now we can calculate the extra-costs (EC), in relation to the electricity mix of each region, for the electricity produced by the new PV systems installed at a year t during a certain year τ of their

lifetimes, that is

$$EC(t,\tau) = (LCOE(t) - LCOEMIX(\tau))E(t,\tau) \quad (9)$$

where $LCOE(t)$ is the $LCOE$ for the new PV systems installed at year t (see Eq. (2)), and $LCOEMIX(\tau)$ is the compound average $LCOE$ of the electricity mix of each region (world, EU-27, USA or China), for a year "τ" greater or equal than "t".

For the calculation of the total extra-costs incurred during a certain year "τ", $EC(\tau)$, we should take into account the electricity produced by all the PV systems installed during the previous years, i.e., in the interval from 2013 to "τ", and consider repowering when necessary. Therefore,

$$EC(\tau) = \int_{2013}^{\tau} EC(t,\tau)dt \quad (10)$$

Finally, we can calculate the total extra-costs during the period 2013–2050 in order to accomplish the three scenarios considered in this work for PV systems. These total extra-costs should be given by

$$EC = \int_{\tau=2013}^{2050} EC(\tau)d\tau = \int_{\tau=2013}^{2050}\int_{t=2013}^{\tau} ((LCOE(t) - LCOEMIX(\tau))E(t,\tau)dtd\tau \quad (11)$$

where $LCOE(t)$ is determined by Eq. (2) and $E(t,\tau)$ is given by Eqs. (6–8) (notice that the upper limit in the integral of Eq. (11) should be 2035 instead of 2050 in the case of the New Policies Scenario).

We have represented in Fig. 7 the annual extra-costs according to Eq. (10), expressed in 2013 USD billion, to accomplish the three scenarios considered for PV systems in the case of the world, for a real annual growth rate of the electricity mix prices of 0% and 0.5%. The total amount of these extra-costs according to Eq. (11), for the four regions studied in this work (world, EU-27, USA and China), have been summarized in Table 4.

Now we are also prepared to calculate the unit costs per tonne of abated CO_2 emissions due the installation of PV systems. This will be very useful for comparing how efficient are the different scenarios in economic and environmental terms, as well as for determining the most suitable locations for their implementation. The concept of unit emission costs is also very useful for comparing PV systems with alternative technologies for emissions

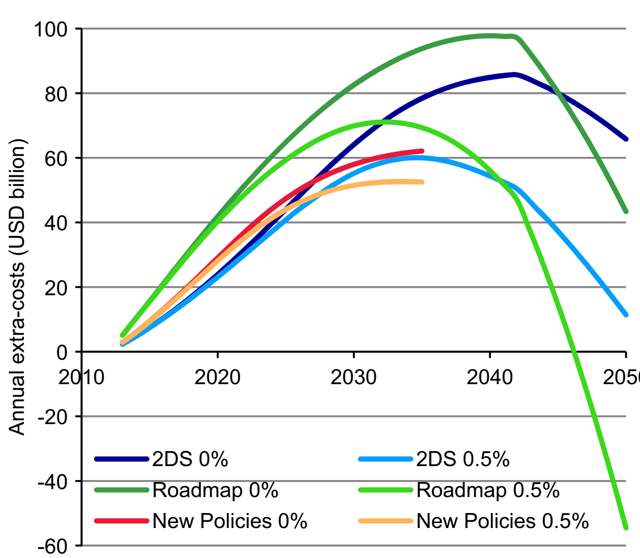

Fig. 7. Annual extra-costs, in 2013 USD billion, to accomplish the three scenarios considered for PV systems, between 2013 and 2050 for the 2DS and Roadmap Scenarios and between 2013 and 2035 for the New Policies Scenario, in relation to world electricity mix and for a real annual increase rate for conventional electricity of 0% and 0.5%.

Table 4
Total extra-costs, in 2013 USD billion, to accomplish the 2DS and Roadmap Scenarios between 2013 and 2050 and the New Policies Scenario between 2013 and 2035, in relation to the mixes of the world, EU-27, USA and China for a real annual growth rate of the cost of conventional electricity of 0% and 0.5%.

Scenario	2DS (2013–2050)		Roadmap (2013–2050)		New policies (2013–2050)	
	0%	0.5%	0%	0.5%	0%	0.5%
World (B$)	2117	1436	2531	1493	902	820
EU-27 (B$)	−195	−1353	−1081	−2837	484	345
USA (B$)	2031	1433	2466	1558	838	767
China (B$)	4526	4234	6214	5770	1386	1351

Table 5
Unit emission costs, in $/t, for the scenarios and regions considered for a real annual growth rate of the electricity mix prices of 0% and 0.5%.

Scenario	2DS (2013–2050)		Roadmap (2013–2050)		New policies (2013–2035)	
	0%	0.5%	0%	0.5%	0%	0.5%
World ($/t)	88	60	73	43	164	149
EU-27 ($/t)	0	0	0	0	138	99
USA ($/t)	86	61	71	45	155	142
China ($/t)	129	121	121	113	171	167

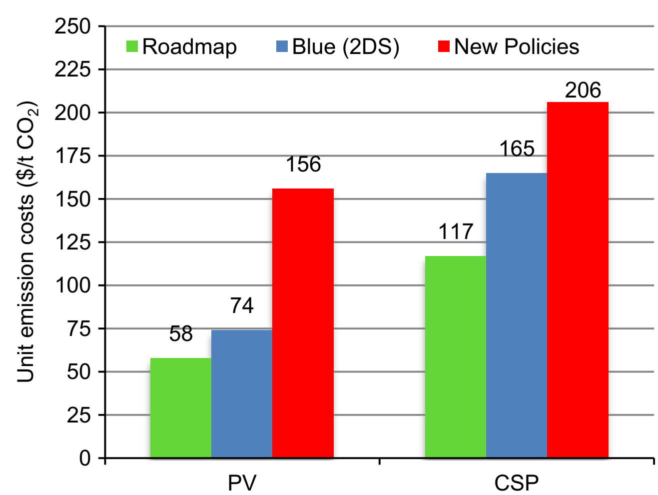

Fig. 8. Average unit emission costs, in USD per tonne of CO_2 saved, due the installation of PV and CSP systems for the 2DS, Roadmap and New Policies Scenarios in the case of the World.

abatement in the power sector, and also for comparing them with the carbon emissions market price. In order to estimate the unit emission costs (UEC) per tonne of avoided CO_2, we just have to divide the total extra-costs to accomplish the scenarios (EC), given by Eq. (11) and summarized in Table 4, by the total CO_2 saved emissions, given by Eq. (5) and represented in Fig. 6. Accordingly, we present in Table 5 the results obtained for the unit cost per tonne of abated CO_2 ($/t) for the three scenarios, in relation to the electricity mixes of the world, EU-27, USA and China, and for two different real annual growth rates of the cost of the electricity mix. Additionally, in Fig. 8 we represent the average unit emission costs for PV systems obtained for each scenario in the case of the world. The results obtained are also compared with the average values that we have calculated for concentrating solar power (CSP) electricity generation based on the data from a previous publication [28].

6. Discussion of results

6.1. Annual and total CO_2 saved emissions

The different yearly-paths followed by the annual CO_2 emissions avoided for each scenario that we have calculated in Section 4 (see Fig. 5), lead to quite diverse total amounts of avoided CO_2, as it can be observed in Fig. 6. For instance, the total emissions savings during the period 2013–2050 are around 50% higher in the Roadmap Scenario than in the 2DS. This is mainly due to the continuous growth of the PV systems deployment in the Roadmap Scenario (see Fig. 3), whilst for the 2DS Scenario the fastest evolution just occurs between 2020 and 2040. We cannot directly compare the New Policies Scenario with the previous ones, since it is only applicable until 2035; however, it shows practically the same annual emission savings than the 2DS Scenario up to 2025, although from there on its pace is observed to slow down.

The composition of the different electricity mixes that we have considered in our work (world, EU-27, USA and China) has a large influence on our estimations for the CO_2 emission savings. As it can be concluded from Fig. 6, PV deployment is obviously more efficient, in environmental terms, when the systems are installed in those locations where the original power generation installations have higher associated emissions per kWh produced. Consequently, for the same scenario, total emission savings in the USA and China are around 50% higher and more than double, respectively, than the corresponding to the EU-27.

The results that we have obtained in this work match relatively well the estimations of the IEA for each scenario. For instance, for the 2DS Scenario, our calculations for both the emissions avoided during 2050, of around 1 Gt/yr, and the total amount avoided between 2013 and 2050, of 24 Gt (see Fig. 5), agree fairly well with the IEA estimations [23]. This would imply that solar PV would be responsible of around 6% of the cumulative CO_2 emissions reductions in the power sector in the 2DS Scenario. For the Roadmap Scenario our calculations for the annual CO_2 emissions avoided during 2050, in the case of the world (see Fig. 5), of around 2.4 Gt/yr, are comparable with the IEA estimations of 2.3 Gt/yr in 2050 [25]. As for the New Policies Scenario, our estimations for the annual emissions saved in 2035 are of around 0.4 Gt/yr (see Fig. 5). Therefore, comparing this value with the IEA appraisals that deployment of renewables would reduce CO_2 emissions 4.1 Gt/yr in 2035 [11], allows us to estimate that the PV contribution would represent around 10% of the annual emission savings attributed to all renewable power resources.

6.2. Annual and total extra-costs

Comparing the annual extra-costs calculated for each scenario (see Fig. 7), we observe that the values obtained for the Roadmap Scenario are generally higher than those corresponding to the 2DS. However, from 2040 onwards the situation reverses, due to the fact that grid parity is reached sooner in the Roadmap Scenario than in the 2DS. Consequently, the total extra-costs (2013–2050) for emissions abatement in the Roadmap Scenario are not much higher than for the 2DS, as it can be observed in Table 4, even though the total CO_2 emissions saved in the Roadmap Scenario are considerable greater (see Fig. 6). This obviously can have important consequences on the average unit emissions costs associated to each scenario (see also Fig. 8).

We can also appreciate in Fig. 7 how sometimes the slope of the curve that represents the annual extra-costs becomes negative. This occurs because grid parity has been already reached (see Fig. 4), which implies that the contribution of the new systems to the annual extra-costs is negative, i.e., the electricity produced by the new PV systems would be cheaper than that supplied by the grid. It can also be observed in Fig. 7 how in the case of the Roadmap Scenario, for a real annual growth rate of conventional electricity prices of 0.5%, a determined year will be reached when the annual extra-costs become negative (around 2046). This can be attributed to the fact that from this year on, the annual money savings begin to outweigh the expenditures. Finally, we can appreciate in Fig. 7 the influence of the repowering, introduced by means of Eqs. (6)–(8), whose effect can be observed from 2043 onwards. The observed savings caused by repowering are due to the fact that the new systems would have a considerably lower *LCOE* than the old ones that are replaced.

If we compare the total extra-costs, summarized in Table 4, for the three scenarios and the four regions considered in this work, we can appreciate the strong influence of the cost of conventional electricity. In effect, in those regions with higher conventional electricity costs, like the EU-27, the total cumulative extra-costs, during the 2013–2050 period, can even be negative. This is because the total money savings caused by the implementation of the new PV systems, once the grid parity is reached, are higher than the total expenditures incurred before grid parity. Furthermore, it can be observed that a conventional electricity cost annual growth rate of only 0.5% has a large influence on the values of the total extra-costs for all the scenarios considered.

Next, we can compare the results obtained for the unit costs of the avoided CO_2 emissions due to the installation of PV systems according to the scenarios and regions studied in this work, which have been summarized in Table 5. From our results, we highlight the fact that the more ambitious the scenario, in terms of annual electricity production, the lower the unit emission costs, which is an obvious consequence of the mathematics of the learning curves. Thus, the unit emission costs in the case of the world are 73 (43), 88 (60) and 164 $/t (149 $/t) for the Roadmap, 2DS and New Policies Scenario, respectively (notice that the values between brackets correspond to a real annual growth rate of conventional electricity costs of 0.5%). The New Policies Scenario has considerably higher unit emission costs since it is only defined until 2035, and therefore it does not take advantage of the lower costs of the new PV systems from 2035 onwards, as it is the case for the 2DS and Roadmap Scenarios.

Comparing the results obtained for the different regions (World, EU-27, USA and China), we can appreciate the large influence of the cost of conventional electricity. Indeed, in regions like the EU-27, with the highest conventional electricity prices, the unit emission costs for PV systems would be zero for the 2DS and Roadmap Scenarios (see Table 5). This is so because during the period considered (2013–2050) the economic savings are higher than the expenditures, since grid parity would be reached relatively early. Actually, as it can be observed from Table 5, the differences between conventional electricity costs are more significant than the differences between the compositions of the electricity mixes. Analogously, it can also be observed the large impact of possible annual increases of the conventional electricity prices on the reduction of the unit emission costs.

Further conclusions can be reached from the results summarized in Table 5. For instance, the marginal CO_2 emission costs given by the IEA [23] for the 2DS Scenario, of 150 $/t, are considerably higher than our estimations for PV systems for this scenario, even in the most unfavourable regions like in the case of China. Consequently, the PV technology would be very suitable in order to accomplish the decarbonization objectives of this scenario. We have also compared, in Fig. 8, the average unit emission costs obtained for solar PV and CSP technologies. We can appreciate that the unit costs for avoided emissions associated to PV systems are around half the values of those corresponding to CSP systems, except in the New Policies Scenario where both technologies present similar costs. This is partly due to the fact that a significant

percentage of the PV systems compete with retail electricity prices, not with wholesale prices, which are considerably lower. However, CSP systems normally include integrated energy storage, which improves power integration to the grid, and consequently can compensate their higher costs. Finally, after comparing our estimations for the unit emission costs for PV systems with the carbon emission prices of the EU emission trading system, that in 2012 was around 10 $/t [14], we conclude that they are clearly insufficient to promote clean power. In this sense, it can be pointed out that highly accredited estimations from other authors assert that social costs of climate change are in the order of 100 $/t [58].

7. Summary and conclusions

In this paper we have developed an analytical method for the calculation of the future (2013–2050) reduction of CO_2 emissions (annual and total) due to the deployment of photovoltaics for power generation, according to the targets for renewable electricity implementation indicated by several IEA Scenarios. Besides, we have developed an analytical method for the calculation of the financial extra-costs incurred by PV deployment, taking as reference the actual electricity mix ("grid averages") in four regional cases: the European Union, United States, China, and the world's average. In our calculation we have taken into account not only the usual parameters (solar irradiation, costs of the systems, discount rate, etc.), but also others often ignored, as the time degradation of the solar modules, external costs like the emissions assigned to the life-cycle of the renewable systems themselves, and repowering and substitution of systems after their life-time is reached.

A careful analysis of the results presented in this paper allows us to reach the following conclusions: (i) the more ambitious the scenario is, in terms of PV deployment, the less the unit emission costs per tonne of saved CO_2 (Table 5). (ii) There is a large influence in costs effectiveness of the electricity mix composition of the region/country where the PV systems are installed. From this point of view (Fig. 6), it is much more economically efficient to install the PV systems in those locations, or countries, with very contaminating power generation plants. Analogously, it will be more cost-effective to deploy the PV generation systems in those areas where the conventional electricity costs are higher. (iii) The obtained data on the retrofitting of old plants (Fig. 7), once their life-time of 30 years is over, show that the annual extra-costs are reduced considerably as a consequence of the lower *LCOE* costs of the new PV systems replacing the old ones. (iv) Unit emission costs of PV systems are very competitive if we compare them with other possible technologies for decarbonization, like CSP (see Fig. 8). (v) The results of this work on the reduction of CO_2 emissions, and calculation of the corresponding extra-costs, can be of great interest in energy planning policies, especially in matters related to the integration of PV into the grid, establishment of tariff-ins, decarbonization of the power sector, etc.

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